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Numerical Investigation on Load Bearing Capacity of Pervious Concrete Piles as an Alternative to Granular Columns

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Abstract**—**Pervious concrete combines considerable permeability with adequate strength, which makes it very beneficial in pavement construction and also in ground improvement projects. In this paper, a single pervious concrete pile subjected to vertical and lateral loading is analysed using a verified three dimensional finite element code. A parametric study was carried out in order to investigate load bearing capacity of a single unreinforced pervious concrete pile in saturated soft soil and also gain insight into the failure mechanism of this rather new soil improvement technique. The results show that concrete damaged plasticity constitutive model can perfectly simulate the highly brittle nature of the pervious concrete material and considering the computed vertical and horizontal load bearing capacities, some suggestions have been made for ground improvement projects.

Keywords**—**Concrete damaged plasticity, ground improvement, load bearing capacity, pervious concrete pile.

I. INTRODUCTION

PERVIOUS concrete has considerable permeability and sufficient strength which makes it very suitable for pavement construction because of the resulting quick rain water drainage, noise absorption, freezing and thawing durability and some other advantages [1]. Pervious concrete can also be used in the construction of parking lots, slope stabilization, artificial reefs, etc. [2]. Because of the growing importance of this relatively new material, there have been a considerable number of researchers investigating the mechanical and hydrological properties of pervious concrete in the past several years.

It has been found that the porosity and the permeability of pervious concrete are directly proportional and substantially higher than normal concrete. However, their strength properties, which are highly influenced by porosity, are much lower [3], [4]; although, a study suggests that some of these weaknesses can be remedied by increasing quantity of small aggregates (4-8 mm) used in the mixture [5]. The addition of fibers has minimal effects on the ultimate strength properties of pervious concrete [6] but their residual flexural capacities can be improved, especially in high porosity conditions. It is also possible to use different substitutions for normal aggregates such as recycled concrete aggregate in pervious concrete mixture, which is investigated in [7], [8]. Despite an appreciable number of papers concerned with the mechanical and hydrological properties of pervious concrete, there are still some deficiencies in the literature such as subjects of requirements for mix design and testing methods, development of standard structural design procedures and most important of all, structural modeling [9].

In recent years, a new application for pervious concrete has come to the attention of researchers. The main idea is that with a combination of adequate strength and also high permeability, pervious concrete piles would become a superior alternative to granular columns [10]-[12]. Despite the strength characteristics of granular columns which are heavily dependent on the confinement provided by the surrounding soil [13]-[16], pervious concrete piles are independent and can even be used in very soft soils [10], [11]. Alongside this advantage, the solid nature of pervious concrete piles results in favorable behavior when they are subjected to severe lateral loads in slope stabilization projects and also during earthquakes, whereas granular columns are very susceptible and fail in direct shear [10], [13].

Numerical modeling is much more cost effective than field and laboratory experimental investigations [17], and considering the increasing trend in using pervious concrete piles in ground improvement projects in the upcoming years, a reliable method for numerical analysis of this kind of piles is strongly needed. Many researchers investigated various aspects of piles made of normal concrete via finite element modeling. While some of them considered linear elastic behavior for concrete material [18]-[21], some other researchers used nonlinear elasto-plastic constitutive models [22], [23].

In this study, a three dimensional finite element code is used to examine the suitability of concrete damaged plasticity nonlinear constitutive model for simulating pervious concrete materials and also study the behaviour of pervious concrete piles under vertical and horizontal loadings. Prior to performing the parametric study, verification of numerical modelings and its parameters was conducted using relevant test data.

II. VALIDATION OF NUMERICAL MODELING PROCEDURE

The final goals of this paper are to evaluate the versatility of

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a concrete damaged plasticity model in simulating failure in pervious concrete material and also studying the behaviour of pervious concrete piles under vertical and horizontal loading by using ABAQUS, three dimensional finite element analysis code. In order to validate the procedure used in the modeling of the pervious concrete piles, soil and the soil-pile interactions, two set of vertical and horizontal experimental load tests on small-scale pervious concrete piles reported by [10], [11] were used.

In the experimental study performed on vertical performance of pervious concrete piles [11], four vertical load tests have been performed, two of which were for comparing stone columns and pervious concrete pile and the other two to investigate the effects of installation method i.e. precasting or installed. Tests were performed in two stacked soil boxes having the dimensions of 1.5 m × 1.5 m × 1.5 m and 1.5 m × 1.5 m × 0.75 m and the vertical reaction frame. Pervious concrete pile used in test unit 3 (precast) of this study was chosen for verification since it had the minimum changes in geometry and surrounding soil through the process of test set up. The pile was 102 mm in diameter and had an embedded length of 1219 mm. The pervious concrete material had a porosity of 12.5%, 28-day compressive strength of 22.2 MPa, an elastic modulus of 15.4 GPa, and also a split tensile strength of 2337 kPa. The soil was classified as well-graded sand according to the unified soil classification system. Detailed geotechnical parameters of the used soil are mentioned in the referenced paper.

For horizontal loading on pervious concrete piles, a soil box having the dimensions of 1.8 m × 1.8 m × 1.8 m and a vertical reaction frame is used [10]. Two different pervious concrete piles i.e. precast and installed are used in this study from which the precast pervious concrete pile is used in verification of the numerical code because of the fact that changes in geometry of the pile and also the surrounding soil was minimized in this piles test setup. The pile was 102 mm in diameter and had an embedded length of 1321 mm. The pervious concrete material had a porosity of 12.5%, 28-day compressive strength of 22.8 MPa, an elastic modulus of 15.1 GPa, and also a split tensile strength of 2707 kPa. The soil was classified as poorly-graded sand according to the unified soil classification system. Detailed geotechnical parameters of the used soil are mentioned in the referenced paper.

Both of the vertical and horizontal load tests were simulated by using the mentioned finite element code. The tensile post-failure stress as a function of fracturing strain is the most important input data in using concrete damaged plasticity model. In this study, inelastic displacement method is used where tensile strength drops to residual amount of 30 kPa in 2 mm inelastic displacement and a tensile damage of 0.95. Inelastic displacement method does not induce numerical problems and it was successfully used by another researcher on quite similar materials to pervious concrete such as lime-cement columns [24]. Fig. 1 shows the numerical validation model geometry for horizontal loading test.

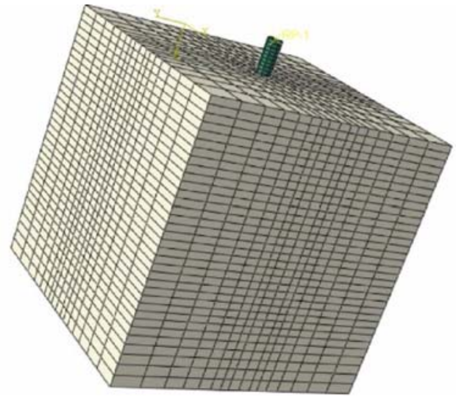


Fig. 1 Numerical validation model geometry for horizontal loading test

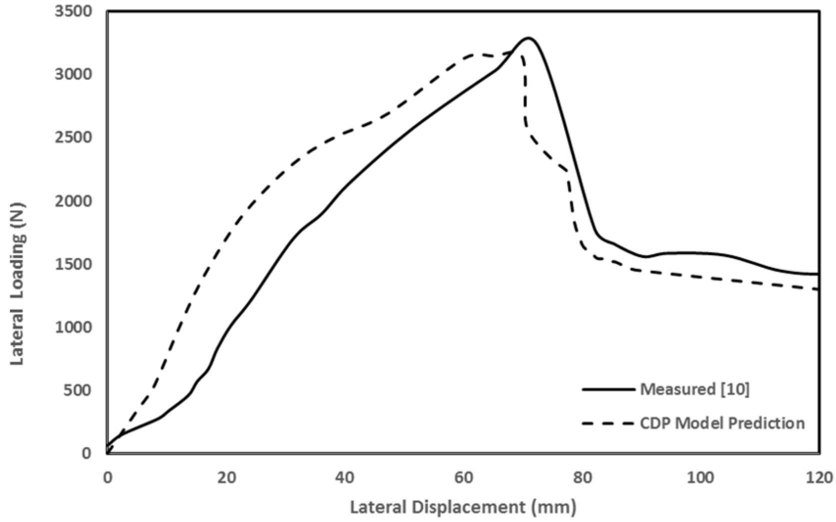


Fig. 2 Computed and measured horizontal load-displacement of small-scale pervious concrete pile [10]

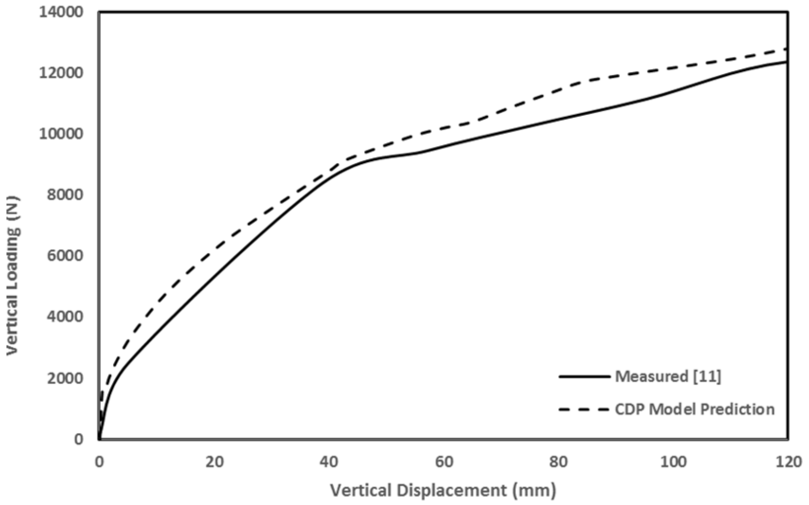


Fig. 3 Computed and measured vertical load-displacement of small-scale pervious concrete pile [11]

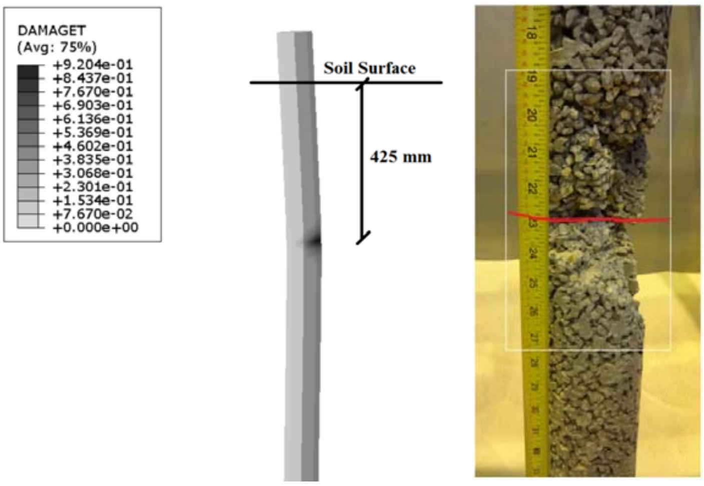


Fig. 4 The comparison between estimated (425 mm) and experimented (470 mm) depth of crack of small-scale pervious concrete pile in horizontal loading [10]

Figs. 2 and 3 show comparative results between computed and measured data for horizontal and vertical load-displacement curves, respectively. Fig. 4 shows the comparison between estimated (tensile damage contour) and experimented depth of crack for horizontally loaded pervious concrete pile. There is a fairly good match between the experimental and numerical load displacement curves and also the error in predicting the depth of crack is acceptable. These findings verify the modeling procedure used in this paper and also indicates the versatility of the concrete damaged plasticity model in accurately simulating failure in pervious concrete material. It is noteworthy that both tests were also simulated using elastic models and dramatic differences had been seen between the measured and elastic model predictions.

III. THREE DIMENSIONAL NUMERICAL ANALYSIS

The most important advantage of pervious concrete piles is that unlike granular columns, they can even be used in soft soils [10]-[12]. In order to investigate this superiority, the soil used in this study was selected as a soft silty soil in which pervious concrete piles used rather than stone column in some ground improvement project reported by [12]. Table I shows physical and mechanical parameters of silty soil. The soil was modeled in saturated condition by using elastic-perfectly plastic Mohr Coulomb criterion.

TABLE I
SILTY SOIL PARAMETERS [12]

Parameter	Silty Soil
Elastic Modulus (kN/m^2)	5000
Cohesion (kN/m^2)	28
Friction Angle	17.8
Poisson's Ratio	0.3
Saturated Unit Weight (kg/m^3)	1980

One of the goals of this study is to gain insight into extent of vertical and horizontal load bearing capacity for pervious concrete piles in a typical soft soil. In order to investigate this less studied topic, three types of pervious concrete with different amount of strength properties which are within a reasonable range of strength reported in the literature, were adopted which are shown in Table II. The elastic modulus of pervious concrete was calculated by an equation reported in [25] and the tensile strength were adopted as a proportion of compressive strength cited in [11]. The pile was modeled by the concrete damaged plasticity model and post peak tension and compression and also damage inputs of all models were appropriately assumed by inelastic displacement method as described in verification section.

TABLE II
RANGE OF PERVIOUS CONCRETE STRENGTH PARAMETERS

Parameter	Low Strength	Medium Strength	High Strength
Compressive Strength (MPa)	10	15	20
Elastic Modulus (MPa) [25]	14968	18333	21465
Tensile strength (MPa)	1.2	1.8	2.4

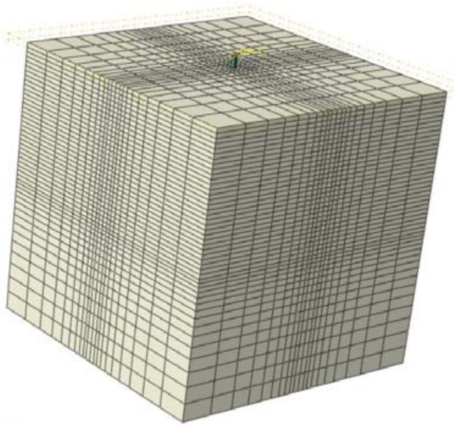


Fig. 5 The finite element mesh adopted in this study

Fig. 5 shows the three dimensional finite element mesh and boundary conditions assumed in this study. All the peripheral sides of the geometry were fixed horizontally and the base was restricted in all directions. Soil layer and the pile were modeled by C3D8R elements, and in order to minimize the effects of boundary conditions, the models were assumed with quite large dimensions i.e. 20 m in width, 20 m in length and depth of 30 m. Since the pervious concrete piles are used in ground improvement projects for expediting consolidation and subsoil reinforcement, the water table was assumed at ground surface.

IV. ANALYSIS OF THE RESULTS

A. *Effects of Pervious Concrete Strength*

The ultimate bearing capacity of a single stone column is considered as a load corresponding to a settlement equal to 10% of its diameter [26]. For this reason, the load-displacement curves are presented up to 60 mm deformation in both vertical and horizontal loading. The pile was assumed with 0.6 m diameter and 10 m in length. Three different types of pervious concrete presented in Table II were adopted to investigate the effects of pervious concrete strength on load bearing capacity and failure mechanism of the piles.

Fig. 6 shows vertical load-settlement for a range of different pervious concrete. As it was expected, strength properties of pervious concrete do not have any effects on ultimate vertical load bearing of piles. All of the piles with various strength had the same 717 kN ultimate vertical bearing capacity.

Fig. 7 shows horizontal load-displacement for a range of different pervious concrete strength. Generally, pervious concrete piles reach a peak of ultimate horizontal load bearing, after which the flexural failure occurs and the propagation of cracks cause it to drop to a gradually increasing residual horizontal load bearing. The higher the strength of pervious concrete, the more the ultimate and residual horizontal load bearing and also failure displacements is. Fig. 8 shows tension damage contour which is an indication of cracking in the body of unreinforced pervious concrete piles. It can be seen that in piles with lower strength, flexural failure occurs in shallower depth and with increasing the pervious concrete strength, the cracking depth increases.

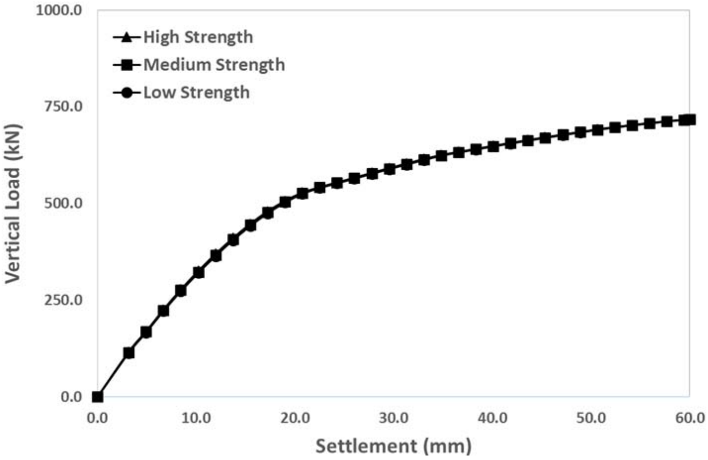


Fig. 6 Vertical load-settlement for various pervious concrete piles

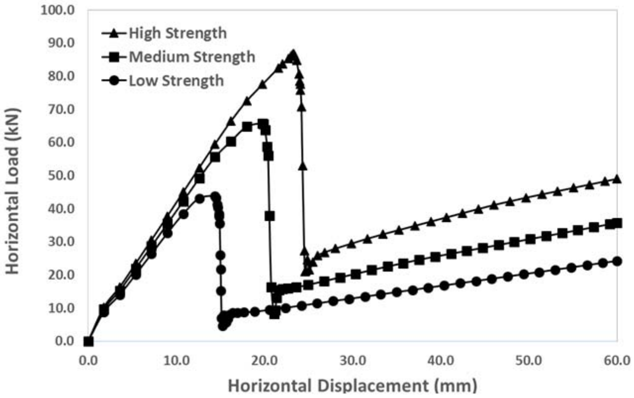
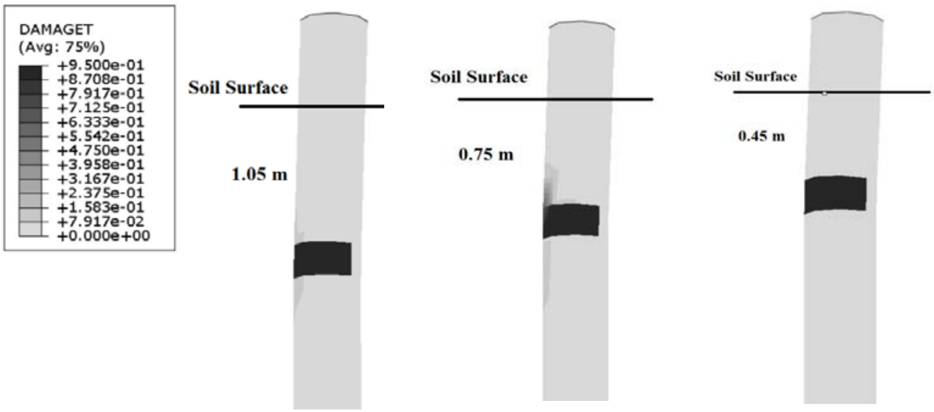


Fig. 7 Horizontal load-displacement for various pervious concrete piles



(a) (b) (c)

Fig. 8 Depth of pervious concrete pile affected by cracking under horizontal loading with different strength (a) high strength (b) medium strength (c) low strength

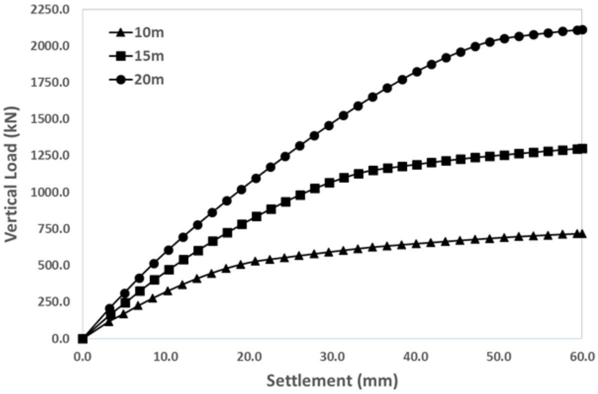


Fig. 9 Vertical load-settlement for pervious concrete piles with different length

B. *Effects of Pervious Concrete Pile Length*

To further investigate the load bearing capacity and failure mechanism of pervious concrete piles, two additional lengths of 15 m and 20 m were analysed while keeping the pervious concrete as high strength.

Fig. 9 shows vertical load-settlement for a range of different pervious concrete pile lengths. As it was expected, with increasing the length of pervious concrete piles to 15 m and 20 m, the ultimate vertical load bearing capacity grows by 81% and 194%, respectively. However, as it was shown in Fig. 10, the ultimate and residual horizontal load bearing of pervious concrete piles are not affected by pile length. According to Fig. 11, flexural failure occurred in quite same depth in all piles with different length and for this reason there was no chance of full mobilization of surrounding soil strength especially and deeper parts of the piles.

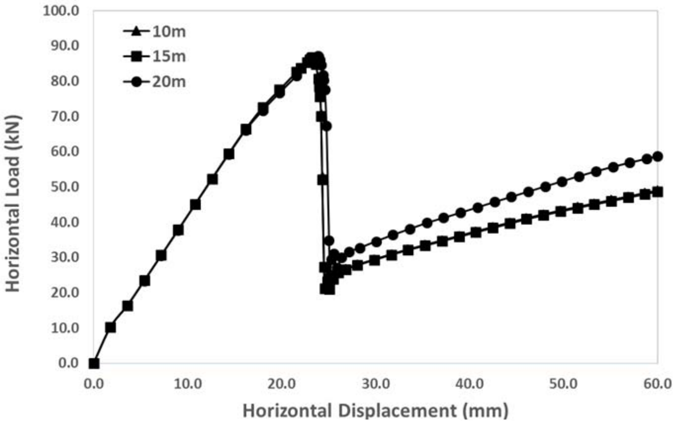
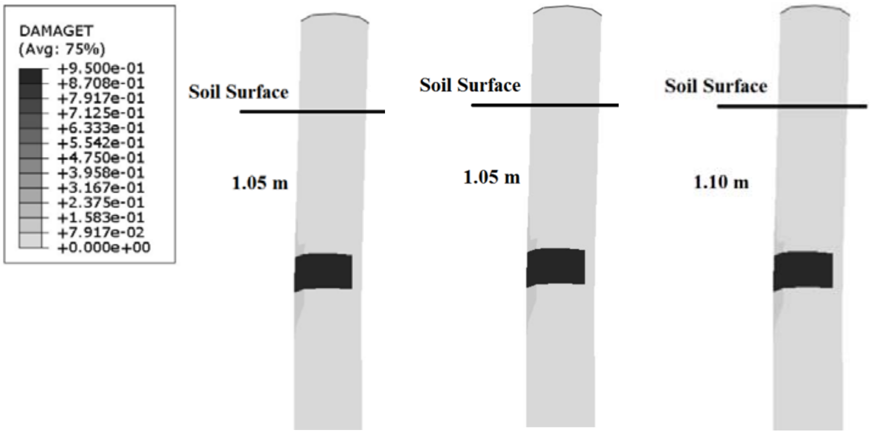


Fig. 10 Horizontal load-displacement for pervious concrete piles with different length



(a) (b) (c)

Fig. 11 Depth of pervious concrete pile affected by cracking under horizontal loading with different length (a) 10 m (b) 15 m (c) 20 m

V. CONCLUSION

This paper investigated the suitability of using concrete damaged plasticity for simulating pervious concrete material and also it was aimed to gain insight into load bearing capacity and failure mechanism of a single unreinforced pervious concrete pile in a saturated soft soil. Based on the assumed geometrical configurations and soil parameters, the following conclusions can be drawn.

1- Pervious concrete material has a brittle nature and cannot be simulated numerically by linear models. However, concrete damaged plasticity is a versatile nonlinear model which can accurately simulate failure and deformation in structures constructed with pervious concrete such as pervious concrete pile.

2- Pervious concrete pile material can have a wide range of strength properties which have an inconsiderable influence on vertical load bearing. On the other hand, horizontal load bearing of pervious concrete piles are heavily depended on pile material strength and for this reason it is suggested that high strength pervious concrete should be used in ground improvement projects where lateral loading is imposed on piles such as beneath embankments and the areas with high seismic risk.

3- The ultimate vertical load bearing of pervious concrete piles increases dramatically by adopting longer length. However horizontal load bearing of piles are not affected by piles length because of shallow flexural failure.

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